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CASE STUDY

Sustainability index analysis of the black soldier fly (Hermetia illucens) cultivation from food waste substrate

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ABSTRACT

BACKGROUND AND OBJECTIVES: Most Food Waste (FW) is dominated by domestic activities consisting of large numbers of organic pollutants, such as nitrogen and phosphate potentially hazardous to the environment. Domestic waste can be used as a feed source in Black Soldier Fly (BSF) cultivation with utility in pollutant removal, animal feed production, and compost fertilizer. Therefore, this study aimed to determine sustainability of larvae from BSF cultivation by calculating and analyzing index.
METHODS: Data collection was conducted using the scientific judgment of experts and business actors in BSF through Focus Group Discussion and the filling out of questionnaires consisting of 31 attributes connected with environment or ecology, economics, social, and technology dimensions. Furthermore, the data were calculated using the multi-dimensional scale approach with rapid appraisal software. Sustainability status and leverage attributes were analyzed by Monte Carlo analysis, and alternating least-squares algorithm.
FINDINGS: Sustainability index for larvae of BSF production was 89.69%. The result suggested that the technique in several stages of operation including waste collection, cultivation, harvesting, and commercialization contributed to sustainability development when the elements of strength of each dimension are considered. From the analysis of the four dimensions, economic dimension had 100% or maximum leverage value. The environmental and social dimensions had the same leverage values of 92.02%, while the technological dimension had 74.74%. The results indicated that management experiences and techniques, potential for odor generated, family member involvement, productivity level, and managers level, warrant further attention to improve sustainability of BSF production.
CONCLUSION: Production, productivity, land conversion, and population were identified as significant or dominating factors impacting the supply framework of BSF production by the intended investigation inside the display ponders. Therefore, study should be encouraged to effectively integrate BSF biomass as a value-added component in an ideal environmental, social, economic, and technical system. The results are significant in providing insights into the possibility of feasible BSF biomass production in Indonesia, which can inform government policies and programs.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
71	5	6

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INTRODUCTION

In 2022, Indonesia was estimated to generate 13 million tons of Food Waste (FW) annually, equivalent to 115-184 kg/capita/year. This resulted in losses of about USD 14.2 billion to USD 36.7 billion, equivalent to 4-5% of the annual Gross Domestic Product (GDP) (Bappenas, 2022). In addition to the enormous costs of processing, FW results in several environmental problems, including the use of landfills, odors, and the production of leachate and gas (Rehman *et al*., 2023). According to Food and Agriculture Organization (FAO) study, about 33% of all food produced and consumed is lost or wasted, equivalent to 1,300 million tons of waste per year. This means that the resources needed to produce food are also wasted, with the resulting emissions (Aziz *et al*., 2022). However, burning FW decreases its value economically, and can have negative health and environmental effects, such as dioxin release (Roy *et al*., 2023). Increased pesticide usage, biomass burning, and FW contribute significantly to an estimated 23% of total annual greenhouse gas emissions (Golasa *et al*., 2021). To address this, it is vital to find cost-effective and ecologically beneficial alternatives (Roy *et al*., 2023). The treatment of FW has become a critical concern on a global scale due to the significant expenses associated with environmental management (Aziz *et al*., 2022). Furthermore, composting has become an important approach to FW management because it can reduce the amount and weight while providing non-hazardous, stable, and nutrient-rich soil stabilization materials (Roy *et al*., 2023). The possibility of using insects as a food source (Hoang Ly *et al*., 2023) and a resource for environmental remediation has also resulted in the development of insect breeding (Balaraman *et al*., 2023) and bioconversion entrepreneurs (Zang *et al*., 2022). One of these insects, BSF (*Hermetia illucens* L.), is essential in developing a circular economy in agri-food production systems (Cohn *et al*., 2022). BSF can eat a variety of organic compounds and ingest more than twice the feed of its weight (Surendra *et al*., 2020). The larvae may alter different organic substances (Manojkumar et al., 2023), recover nutrients, and reduce the biomass of organic waste by 50–60% (Franco *et al*., 2021). Meanwhile, BSF Larvae (BSFL) create a highly useful protein biomass by converting an organic molecule, reaching 40–50% (Rini, 2021). BSF frass is also a beneficial by-product of composting in addition to protein larval biomass (Luperdi *et al*., 2023). Depending on the composting substrate used, BSF frass of the experiment is collected after 9 to 23 days and may weigh more than 33% of the original weight of substrate (Basri *et al*., 2022). Furthermore, the use of organic waste for the process is a sustainability and cost-effective means of resource recovery, which can produce value-added products and create business opportunities in the industrial sector (Rehman *et al*., 2023). BSF can also compost organic waste, and convert it into biomass. The development is controlled by substrate nutrition, Potential of hydrogen (pH), temperature, moisture content, Relative Humidity (RH), and light intensity, hence resulting in difficult cultivation. Protein and fat are crucial nutrients for BSF development (Aziz *et al*., 2022), which may devour more than twice its body weight and feed on a variety of organic compounds (Surendra *et al*., 2020). Additionally, the larvae can change various organic components into nutrients and reduce the biomass of organic waste by 50–60% (Franco *et al*., 2021). According to Ermolaev *et al*., (2019), methane emissions from FW composted by fry larvae were 99.5% lower than those from windrow composting. Mertenat *et al*., (2019) also reported that methane levels from the use of BSFL to treat kitchen trash were comparable to those measured in the air. However, (Bava *et al*., 2019) did not detect the gas emissions following co-product treatment with BSFL. Guo *et al*. (2021) also stated equivalent findings when reporting the emission levels below the detection limit of 100 ppm. Table 1 presents data on methane emissions resulting from the use of different substrate. The concept of circular economy is rooted in waste management through the use of BSFL due to its ability to promote circularity, close the loop, and transform waste into valuable resources. (Lopes *et al*., 2022).

BSF works to lower gas emissions (Gao *et al*., 2019) and FW (Giannetto *et al*., 2020) with expected larval feed conversion values of 1.5 to 12.5. Therefore, in the prepupa phase, the larvae are expected to reach a length of 27 mm and a width of 6 mm (Lievens *et al*., 2021), with body weights ranging from 113 to 225mg (Gligorescu *et al*., 2019). The widespread use in waste management occurs because it can lead to the conversion of low-quality carbon sources and produce high-quality larval biomass. After undergoing metamorphosis, BSF adults do not possess a mouth

Table 1: Comparative data on methane (CH_4) emission reduction per kilogram of the treated substrate from bioconversion of different substrate by BSFL

Substrate	Moisture (%)	pH	Amount of substrate (kg)	CH_4 emission substrate ($mgCH_4/kg$)	Reference
FW	75	4.4	0.3-1.1	2.4	Ermolaev *et al*. (2019)
Kitchen waste	-	-	15	0.4	Mertenat *et al*. (2019)
FW (90%) and rice straw (10%)	65	3.0-11.0	1.2	0.2-2.6	Pang *et al.* (2020)

Table 2: Proximate composition of BSF biomass

Material	Composition (%)	Reference
Crude protein	30–52	Surendra *et al.*, 2020
Fat	15–50	Surendra *et al*, 2020; Franco *et al.*, 2021; Mai *et al.*, 2019
Carbohydrates	8–24	Soetemans *et al.*, 2020
Amino acid Essential	40.54-40.89	Huang *et al.*, 2019
Non-Essential	59.11-59.46	Huang *et al.*, 2019
Glutamic acid	12.2	Wang *et al.*, 2020
Aspartic acid	10.3	Wang *et al.*, 2020
Leucine	7.7	Wang *et al.*, 2020
Lysine	7.4	Wang *et al.*, 2020
Arginine	6.2	Wang *et al.*, 2020
Phenylalanine	6.2	Wang *et al.*, 2020
Proline	6.2	Wang *et al.*, 2020
Glycine	5.4	Wang *et al.*, 2020
Histidine	4.8	Wang *et al.*, 2020
Isoleucine	4.8	Wang *et al.*, 2020
Threonine	4.5	Wang *et al.*, 2020
Serine	4.1	Wang *et al.*, 2020
Methionine	0.6	Wang *et al.*, 2020
Cysteine	0.5	Wang *et al.*, 2020

and are incapable of feeding, rendering the lifespan to less than a week. Due to the absence of a mouth, fly cannot act as a vector for disease transmission (Lievens *et al*., 2021). Male BSF typically mates at the age of three days and dies shortly after. On the other hand, female BSF lay eggs three days after mating and typically produce between 500-1,000 eggs before dying. The eggs hatch after three days and grow into prepupa in 18 days. Subsequently, it develops into a pupa, and metamorphoses into a fly for 15 days, then mates and dies after three days as an adult. The life cycle of BSF is short at 45 days and does not have a mouth, or perch on garbage. Therefore, they are clean fly and are not vectors of disease. In contrast, ordinary fly eat and perch on trash. These fly possess a wide range of mobility and can spread disease through feces attached to their mouth and feet. They are small in size and become larvae in only 4-7 days, with a longer pupa phase of 10-20 days. In addition, essential and non-essential amino acids (Kawasaki *et al*., 2019), as well as significant amounts of polyunsaturated fatty acids are found in BSFL (Gao *et al*., 2019). BSFL proximate has the composition as shown in Table 2.

Solid waste engineers have reevaluated and designed waste management plans using alternative processes due to environmental concerns related to FW composting. Some of the processes used to treat FW in the past 20 years have been approved by the solid waste sector (Aziz *et al*., 2022). Meanwhile, the potential for FW utilization is quite large because of the characterization of useful materials, as shown in Table 3. Several studies have reported that the composition of FW varies in terms of its organic components such as protein, and carbohydrates, namely starch, cellulose, hemicellulose, lignin, fat, and organic acids (Suhartini *et al*., 2022). Although the government typically bears the cost of waste processing in high-income nations, the situation is different in low-income nations where limited resources hinder the development of trash management infrastructure (Rindhe *et al*., 2019).

Table 3. Characteristics of FW and analytical measures (Suhartini *et al.,* 2022)

Parameters	Value	Analytical Measurement
TS (percent wet weight; % ww)	22.1	American public health association (APHA) method
VS (% ww)	20.4	APHA method
MC (% ww)	78.9	APHA method
VS (percent total solid; %TS)	92.2	VS divided by TS multiplied with 100
pH	5.92	Digital pH meter
Crude fat/ lipids (percent total solid, %TS)	31.8	NA*
Crude protein (%TS)	15.5	TKN multiplied with a factor of 6.25
Carbohydrate (%TS)	41.6	NA*
C (%TS)	50.84	Elemental analyzer
H (%TS)	7.2	Elemental analyzer
N (%TS)	1.8	Elemental analyzer
S (%TS)	0.24	Elemental analyzer
O (%TS)	32.03	By the difference of 100 minus C, H, N, and S concentration
Cellulose (%TS)	4.7	Automatic cellulose analyzer
Hemicellulose (%TS)	10.05	Automatic cellulose analyzer
Lignin (%TS)	2.12	Automatic cellulose analyzer
C/N ratio	28.2	Calculation

*Not applicable (NA)

Waste transportation and collection account for more than 70% of the costs (Roy *et al.,* 2023). In developing nations, biodegradable organic waste consists of 50 and 80% of municipal garbage production (Rehman *et al.,* 2023). Furthermore, Mahmood *et al.,* (2021) claimed that more marketing opportunities, a limited incentive system, and a lack of legislative backing from the government are barriers to mainstreaming biowaste processing. Evaluation of sustainability of FW composting process is possible by calculating sustainability index using Multi-Dimension Scaling (MDS). Meanwhile, the instruments that enable the evaluation are increasingly needed since the importance of sustainability is progressively acknowledged. A statistical analysis tool known as MDS describes patterns of similarity or resemblance that are close to one another. MDS can convert scientific assessments of their opinions or preferences into distances represented on a multi-dimensional scale. It formally refers to a collection of statistical methods that simplify preference information by providing a numerical representation of the underlying relationships between groups (Wan *et al.,* 2021). In this situation, MDS can translate and develop the opinions or preferences of respondents regarding BSF cultivation themes into sustainability index. This tool has broad applicability in the management of natural resources, marketing, political science, sociology, and ecology. Study on MDS method has been widely used for various objects in agribusiness (Ningsih *et al.,* 2021), natural resources (Narendra *et al.,* 2019), and tourism (Saputro *et al.,*2023). However, the aims of the study were almost similar in providing recommendations and considerations for decision-makers in the framework of sustainability development. The current study aims to assess the feasibility of a sustainability BSF production supply system. Previous analysis related to sustainability of agricultural products using MDS method are presented in Table 4.

The use of insects as a source of protein has been widely discussed around the world. The quality and quantity of fly larvae development media greatly affect the nutrient content of the body and the survival at each instar and subsequent metamorphosis stage (Suardi *et al.,* 2022). Efforts to obtain alternative sources of protein are meaningless when the raw materials cannot be mass-produced on an industrial scale. Meanwhile, BSFL development media based on organic waste is an important factor in the production process because it does not compete with human needs. The type of FW media produces the highest water, fiber, and carbohydrate content in BSFL compared to vegetable and fruit waste (Andari *et al.,* 2021). Since Indonesia is estimated to generate 13 million tons of FW annually, equivalent to 115-184 kg/capita/year (Bappenas, 2022), then the production of maggot larvae in a sustainability

Table 4: Previous study utilizing MDS analysis

No.	Title/Topic of Study	Dimensions	References
1	Using MDS preference plot as visual analytics of data	Environmental, social, economic	(Zhang and Ding, 2023)
2	Policy-related biodiesel sustainability in Indonesia	Ecological, social, economic	(Dharmawan *et al.,* 2020)
3	Assessing sustainability of Plants and Facilities	Ecological, social, economic	(Narendra *et al*., 2019)
4	The study of social network analysis	Ecological, social, economic, institutional	(Chen and Chen, 2021)
5	Sustainability agricultural development	Ecological, social, economic, institutional	(Suardi *et al*., 2022)
6	Sustainability microalgal biomass production	Ecological, social, economic, technological	(Santoso *et al*., 2023)

manner is very critical. However, sustainability can be affected by environmental (Arifudin *et al.*, 2023), economic (Hanim *et al.,* 2021), social (Herlinda and Sari, 2021), and technological factors (Ginanti and Kusuma, 2020). In this study, the four factors were studied to determine sustainability index in providing recommendations to increase maggot production. Many studies on the potential for sustainability of BSF cultivation have been reported but none has analyzed index using MDS. Therefore, this study hypothesizes that the use of FW for BSF maggot-growing media in addition to reducing pollution also improves the quality. The practical approach of MDS provides information that can assist waste management decision-makers in BSF cultivation businesses. This study also assesses the feasibility of BSF production supply system and seeks to 1) identify the dimensions that influence sustainability index, 2) determine sustainability index for environmental, social, economic, and technological dimensions and 3) pinpoint the key variables influencing BSF production systems. Furthermore, it was performed from November 2022 to March 2023 to determine BSF biomass production by calculating and analyzing sustainability index. This study was carried out in the study group on sustainability and Life Cycle Assessment (LCA) analysis of integrated agricultural production systems, National Study and Innovation Agency, Indonesia from 2022 to 2023.

MATERIALS AND METHODS

Study procedure

The process of data collection was executed through the Focus Group Discussion (FGD) at two distinct locations, namely Biomagg Sinergi International Ltd. situated in the Depok district of West Java, and Giri BSF Malang Ltd. situated in East Java. In addition, questionnaires were administered to seven experts associated with BSF workers, maggot and solid waste experts, and business actors. The FGD was conducted to identify the existing conditions of business actors and support for BSF farming resources at the study site as material for preparing dimensions and sustainability attributes. Furthermore, there were four dimensions, including environment/ecology, economics, social, and technology, and the number of attributes used was 31. These dimensions and attributes are then outlined in a questionnaire with answer choices using a Likert scale. The questionnaire used four dimensions with several attributes, and the expert respondents answered the questions in the questionnaire with a score of 0, 1, and 2 for bad, moderate, and good. Questionnaires on biomass production were made available in BSF and solid waste study communities as well as the scientific opinion of professionals. In addition, MDS approach was used to process and evaluate the data. Rapid appraisal for fisheries software was used to conduct an MDS analysis (Lloyd *et al.*, 2022). The current study examined 31 attributes connected to social, economic, ecological, and technological dimensions. Attributes identified on the environmental dimension are material efficiency, use of chemicals in electricity, fuel, and water, the potential for air and water pollution, utilization of waste (feed scraps, dead maggot remains, BSF bodies), exploitation level of natural resources, potential damage to biodiversity, and spread of disease. Attributes of social dimensions included management education, involvement in cultivation of BSF, the level of economic interests, the potential for mass protests, the possible loss of more labor, the possibility of work accidents, and the possibility of creating jobs for locals. Furthermore, attributes in the economical dimension were

cultivation productivity level, potential increase in business scale and success rate, contribution to improving the welfare of managers/workers, efficiency of obtaining raw materials, and level of market absorption of maggot and compost. Attributes in the technology dimension were the success rate of adopting BSF production system, the level of specialization/expertise/skill required for managers, the availability of production facilities and infrastructure, the potential for technology improvement, and the level of technical sensitivity to the quality and quantity of maggot and compost production.

Data analysis

The value of sustainability status and leverage attributes of BSF cultivation from FW substrate through Rapfish analysis has several steps according to (Lloyd *et al*., 2022). These include a) selecting attributes for the assessment of sustainability status and leveraged attributes of BSF farming technology referring to good benchmarks, b) assessing attributes on an ordinal scale referring to each dimension sustainability criteria, c) compiling an index of sustainability status and leverage attributes of BSF cultivation from FW substrate. Furthermore, analysis results show a) the status or index of each dimension and b) the leverage/sensitive attributes affecting sustainability status of BSF farming technology. The position of sustainability status level can be described in vertical and horizontal ordinates, and represented by a flat line. The lousy and excellent extreme has index value of 0% and 100%, respectively. Meanwhile, the scale of value in sustainability status index of intensive duck-rearing technology ranges between 0-100%. It is only sustainability with a more excellent value of 50%. Sustainability status ordination is an overview of each dimension, referring to the attribute of the dimension. Index value point on the axis (x) reflects sustainability status of intensive duck farming technology, and the ordinate (y) shows the variation in scores. This supplements the ordination analysis by testing the normalization of the S-stress value (S) and squared correlation (R^2) of the model. Furthermore, the model is rated good when the S<0.25% value and R^2 are close to 1. The value of S and the R^2 also determine the need to add attributes and simultaneously reflect the accuracy of the dimensions studied with the actual state. Leverage analysis is used to determine attributes sensitive to sustainability, and analysis selects the attribute with the highest influence on each dimension as a lever factor influencing the value. The most sensitive indicators are indicated by the highest Root Mean Square (RMS) values (Borg *et al*., 2018). Meanwhile, Monte Carlo analysis examines a) the Influence of attribute scoring errors, b) the effect of scoring variations due to differences of opinion or judgments by experts, c) the stability of MDS analysis process, d) data entry errors or the presence of missing data, and e) the high-stress value of MDS analysis results. The system under study is excellent or corresponds to actual conditions when the difference between MDS and Monte Carlo calculation results is less than one. MDS ordination is represented by a circle with variable values, references, and anchors. The x-axis for Good and Bad has a maximum and minimum value of 100 and 0, while the y-axis for Up and Down is half the maximum and minimum attribute scores of 50 and -50. In MDS method, points are plotted for the distance between objects to become proportional to their similarity. In addition, the ordination technique or distance determination is based on the Euclidian distance in n-space using Eq. 1 (Borg *et al*., 2018).

$$d = \sqrt{\left(\left|x_1 - x_2\right|^2 + \left|y_1 - y_2\right|^2 + \left|z_1 - x_2\right|^2 + \ldots\right)} \quad (1)$$

where, configurations of objects or points in MDS are approximated by regressing Euclidian distance (d_{ij}) from point i to j with point of origin (o_{ij}) using Eq. 2 (Borg *et al*., 2018).

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (2)$$

the ALSCAL algorithm is used for regression in the equation, and the method optimizes squared distance (d_{ij}) against data (o_{ij}), which in three dimensions ($_{l, j, k}$) are recognized as S-Stress using Eq. 3 (Borg *et al*., 2018).

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i\sum_j o_{ijk}^4}\right]} \quad (3)$$

where, the Euclidian distance is given a value using Eq. 4 (Borg *et al*., 2018).

$$d_{ijk} = \sum_{a=1}^{r} w_{ka} \left(x_{ia} - x_{ja} \right)^2 \quad (4)$$

RESULTS AND DISCUSSION

MDS method was used to calculate the level of sustainability, where the dimensions and attributes are determined by identifying their influence on sustainability of BSF cultivation. Meanwhile, dimensions and attributes influencing sustainability are determined specifically and temporally (Lloyd *et al*., 2022). The attributes which are indicators of each dimension are the results of experts in the field of BSF cultivation. This study includes environmental, social, economic, and technological dimensions, as well as 31 attributes in total. The data in MDS calculation is the assessment of the attributes asked in the questionnaire, and the list of dimensions and attributes is shown in Table 5.

The features in each dimension were organized into a sheet questionnaire and given to pertinent specialists to obtain their expert opinion on the scientific viability of the biorefinery method employed in the manufacture of BSFL. Additionally, MDS approach of Rapfish software was used to examine the outcomes of the expert evaluations. Table 6 displays the derived sustainability indices for each dimension.

The conditions for sustainability BSF cultivation are influenced by environmental carrying capacity, production input availability, production processes, product processing, marketing of BSFL, and the function of relevant organizations. By considering

Table 5: Dimensions and Attributes of BSF cultivation sustainability

Environmental	Social	Economical	Technological
1. Material utilization efficiency (biodegradable) for the production of BSF and compost 2. Efficiency in the use of chemicals during cultivation process and post-harvest 3. Efficiency in the use of electrical energy and fuel during cultivation and post-harvest processes 4. The efficiency of water use during cultivation process and post-harvest 5. The potential for air pollution (odor) generated 6. The potential for water pollution 7. Utilization of waste, consisting of feed scraps, dead maggot remains, and BSF bodies, produced from maggot cultivation 8. Exploitation level of natural resources (land, plants) for maggot cultivation 9. Potential damage to biodiversity due to the maggot business 10. The potential for the spread of disease due to the existence of a maggot business	11. Management education level 12. Involvement of family members in maggot cultivation 13. Level of business motivation 14. The possibility of widespread unrest brought on by BSF cultivation system 15. Level of knowledge of managers/workers on environmental conservation and restoration 16. Potential for work accidents 17. Potential job creation for residents	18. Maggot cultivation productivity level 19. Production management level 20. Potential increase in business scale/business success rate 21. Contribution to improving the welfare of managers/workers 22. The efficiency of production of raw materials 23. The efficiency level of obtaining raw materials 24. The level of market absorption of maggot production product 25. The market absorption rate of compost production	26. The success rate of adopting the maggot production system for the surrounding community 27. The level of specialization/expertise/skill required for managers 28. Availability of production facilities and infrastructure 29. Potential for maggot cultivation technology improvement 30. The level of technical sensitivity to the quality and quantity of maggot and compost production

Table 6: Sustainability index results for all dimensions with data quality indices

Dimension	Index (%)	Stress	R^2(SQR)
Environmental	92.02	0.131	0.947
Social	92.02	0.137	0.948
Economical	100.00	0.137	0.947
Technological	74.74	0.148	0.948
Average	89.69	0.138	0.947

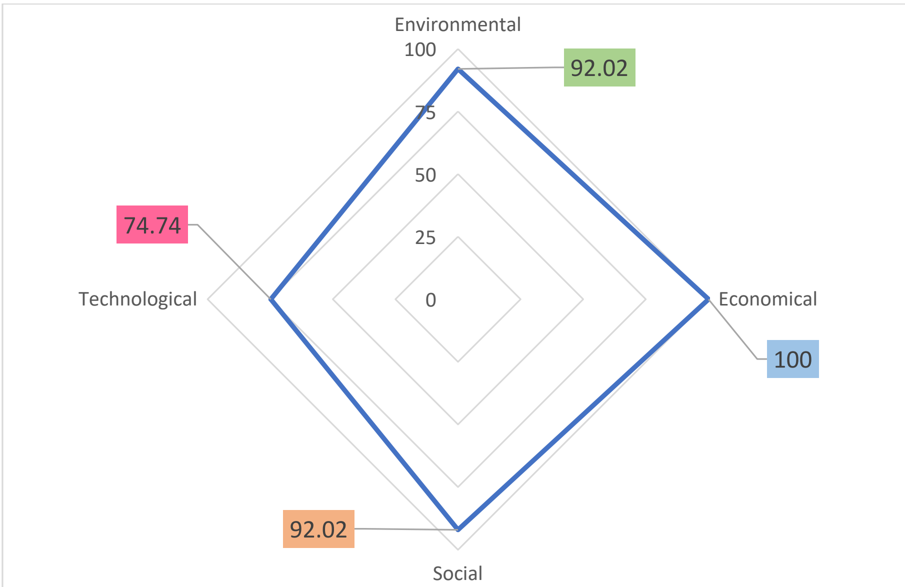

Fig. 1: Sustainability status of BSFL and compost production

these factors and adopting sustainability practices, BSF cultivation can be a more environmentally-friendly and economically-viable alternative to traditional animal feed production (Rehman *et al*., 2023). Fig. 1 displays the findings of MDS study of environmentally friendly BSF farming. A stress value of 0.14 (stress 50%) was observed with comparable findings from the Monte Carlo test between four dimensions as measures of validity and accuracy. Furthermore, BSF production system is in a sustainability condition with a value of 89.69. The technology dimension has the lowest sustainability index but is still in a fairly sustainability condition. The other three dimensions, namely environmental, social, and economic, are included in sustainability category, as shown in Table 6. Leveraging analysis showed that eight attributes have a sensitive influence on BSF production supply system.

Environmental dimension

According to the findings of MDS analysis, the ecological dimension has an index value of 92.02, satisfying the criteria for sustainability. This is a very good index status and is worth maintaining. It has been reported that the utilization of waste can be used for BSF cultivation, with a positive impact on the environment (Iqbal *et al*., 2020).

Leverage analysis shows that 1 attribute has a sensitive influence on sustainability of BSF. It is the potential for air pollution (odor) generated with an RMS value of 7.80, as shown in Fig. 2. For other attributes, the value does not have a significant effect, but attention needs to be paid to maintaining environmental dimension in BSF sustainability. The results reported by Hana and Kriswibowo, (2022) stated that the existence of a waste management program with BSF through corporate social

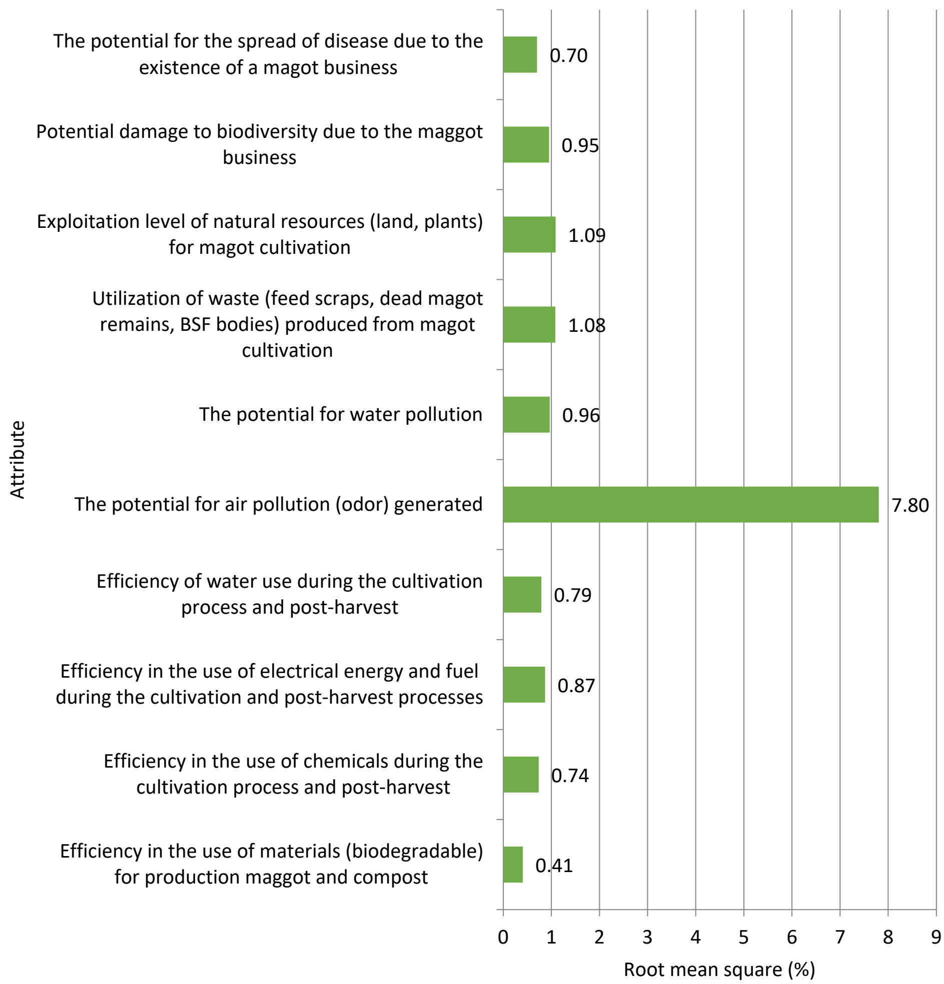

Fig. 2: Leverage of environmental attributes

responsibility (CSR) had a good influence on the quality of the village environment to keep it clean and reduce pollution due to waste. BSFL degrades and consumes different types of organic waste and reduces the initial weight by about 50% in a shorter time than conventional composting methods (Amrul *et al.,* 2022). In addition, the larvae do not cause a pungent odor and no smell complaints are observed (Raksasat *et al.*, 2020). Recently, the use of BSFL to process organic waste has been developing worldwide. The technology has great potential to overcome problems especially related to sanitation infrastructure for waste disposal in tropical countries with low and middle incomes supported by favorable climatic conditions. In addition, BSFL can be used as an alternative feed containing amino acid protein and can be a solution to the high cost of feed (da Silva and Hesselberg, 2020).

Social dimension

Social sustainability can be attained by considering policies that minimize adverse effects on society and support family enterprises. The participation of family members is very important in the characteristics of the social dimension. Many employees working for family businesses are prepared to contribute their resources to lower the financial strain on the enterprise. Furthermore, the structure also enables

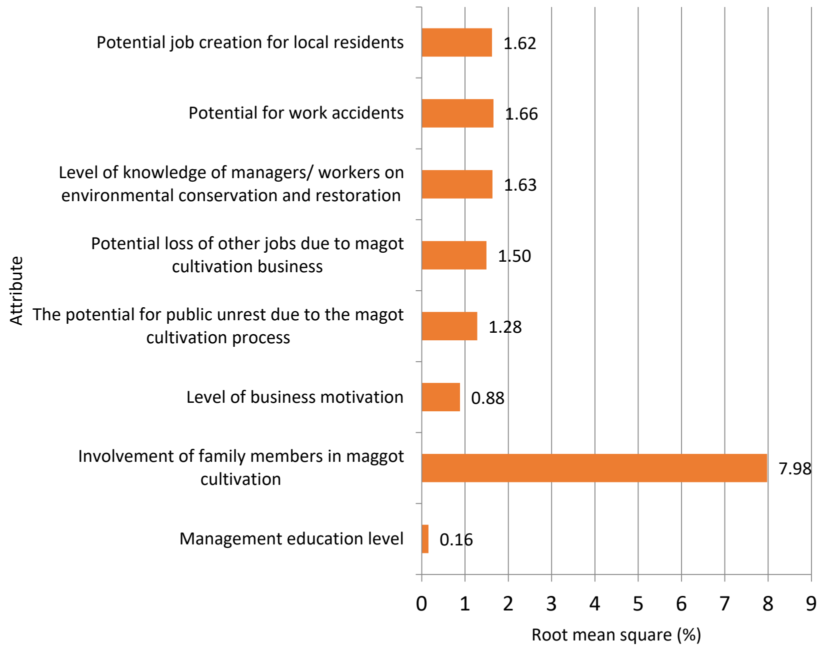

Fig. 3: Leverage of social attributes

management to concentrate more on running the business.

Sustainability index on the social dimension based on MDS analysis shows a value of 92.2, which is included in sustainability criteria. In the leverage analysis, the social dimension consists of 8 attributes. Furthermore, two attributes have the most significant RMS value gap, namely the involvement of family members in BSF cultivation (7.98) and management education level at 7.98 and 0.16, as shown in Fig. 3. The environmental and social dimensions have a direct relationship with the development of BSF cultivation and the same leverage values of 92.02%. The highest attributes for environmental and social dimensions were potential for air pollution generated and involvement of family members in maggot cultivation at 7.8% and 7.98%, respectively. In addition innovation and creativity are required to solve environmental problems in increasing community of family member involvement. Individual involvement in waste management is closely related to the perceptions and expectations, background, social values prevailing in society, and changes in behavior. Factors driving individual involvement are obtained from concern for a problem that directly encourages changes in behavior to be involved in specific actions or programs. Meanwhile, changes in attitude can be made through education programs and other instruments related to the economy. (Fadhullah *et al*., 2022). A study by Noufal *et al*., (2020) showed several factors that influence households in carrying out waste management programs (for example, composting). Some of the challenges identified are the unavailability of land, inadequate time to engage in such practices, absence of practical objectives, unsanitary and unhygienic conditions, and insufficient knowledge on how to effectively implement the program. Furthermore, the involvement of local authorities is needed to support and encourage households through environmental education, training, and awareness campaigns, which provide knowledge on the importance of implementing a program. Fadhullah *et al*., (2022) studied household involvement in waste sorting activities. This study states that education level is an important factor influencing the perception of household waste management. Education has a negative relationship with waste sorting activities, where people with low education are more willing to sort their waste than people with higher education. Possible reasons can be

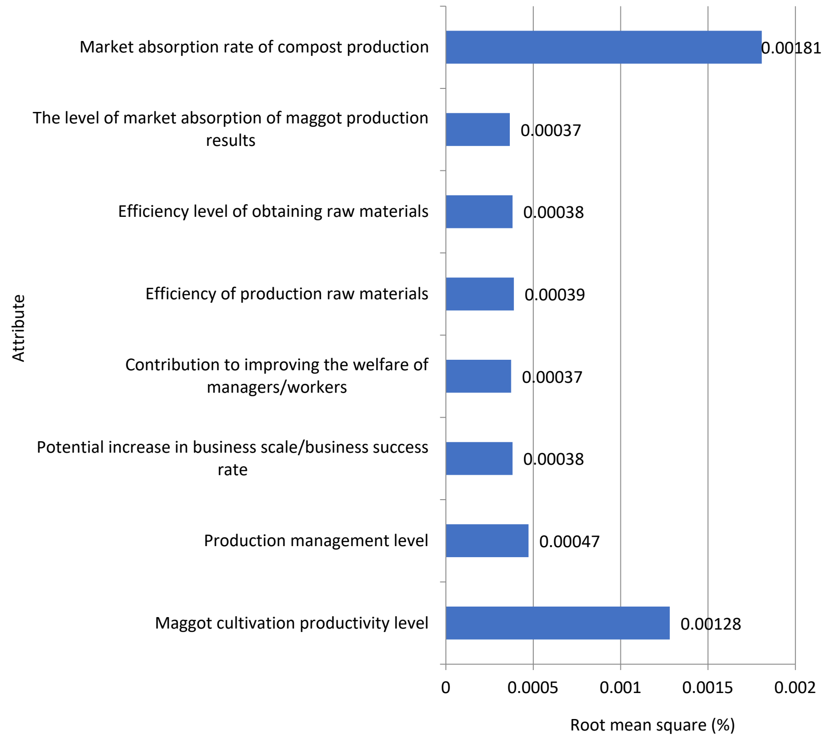

Fig. 4: Leverage of economical attributes

attributed to different lifestyles and time constraints deliberately allocated for waste sorting activities. Garbage is one of the environmental problems faced by almost many countries, hence an effective and sustainability waste management technology is needed. Salam *et al.,* (2022) stated that waste treatment techniques in developing countries do not meet standards. BSF has a good and proven ability to degrade waste and its biotransformation, which provides a potential and economical alternative to recycling biological waste. The results showed that BSFL can improve the quality of the final product and encourage the degradation of organic waste. It can also reduce municipal waste by efficiently degrading organic waste in the environment. From an environmental aspect, BSFL can degrade waste, reducing pollution, and the production process can create job opportunities with an increased value from a social aspect. Furthermore, it can also be used as feed for slag and fish with economic value (Abro *et al.,* 2020). BSFL digests nutrients from waste and produces protein and fat used in animal feed processes and organic fertilizer (Amrul *et al.,* 2022).

Economical dimension

MDS analysis for the economic dimension produces a sustainability index value of 100.00. In this case, the expert assessment of 8 attributes shows that the prospects for developing BSF business are very good. Leverage analysis for the economic dimension shows that there are attributes influencing sustainability, namely market absorption for compost products and the productivity level of BSF cultivation, as shown in Fig. 4. Environmentally compliant BSFL levels can also reduce organic waste and greenhouse gas emissions from landfills to produce sustainability animal feed. Furthermore, it reduces the need for forage production and provides employment opportunities for people in rural areas. The use of BSFL in animal feed production reduces the cost of animal products to become more accessible to low-income consumers. The values correspond to ecosystems and reduce the dependence on fishmeal and soybean meal associated with environmental

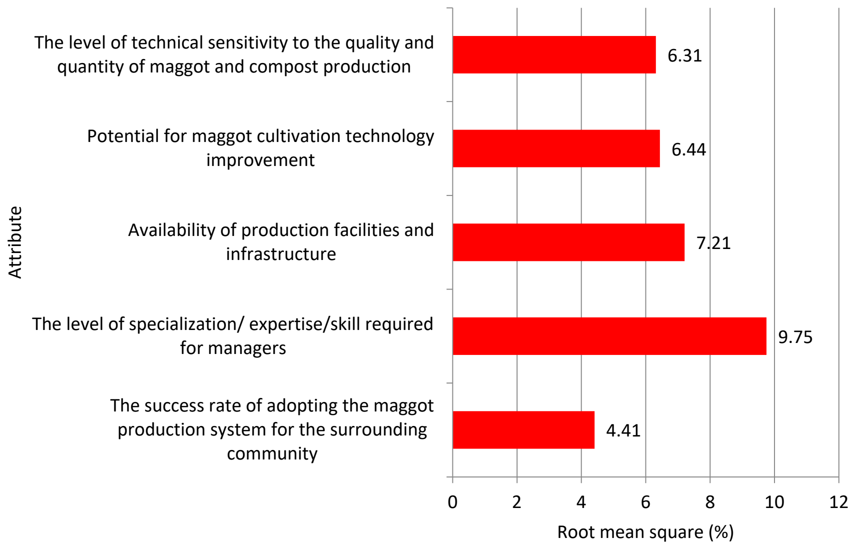

Fig. 5: Leverage of technology attributes

impacts such as overfishing and deforestation. BSFL farming also improves soil health, producing nutrient-rich frass as fertilizer. Finally, these values correspond to technological advances in BSFL farming techniques such as automated harvesting and processing systems to increase efficiency and productivity. Genetic engineering can be used to improve the nutritional content of BSFLs or improve the ability to digest certain types of waste, further improving sustainability of their use.

According to the business and financial analysis conducted, BSF cultivation is quite feasible with a good profit level in a growing, healthy, and advanced condition (Supena *et al.*, 2021). Meanwhile, the availability of capital, labor, and technology affects the efficiency of BSFL produced (Prihartini *et al.*, 2022). On a smaller scale, productivity standards are used to evaluate the conversion of inputs into desired outputs using equipment, facilities, businesses, organizations, systems, or individuals. Sustainability in the production of BSFL is determined by productivity, particularly in terms of obtaining FW as a raw material that satisfies the requirements for a high-quality product. Furthermore, it is also impacted by the degree of management of BSFL generation. Planning, organizing, directing, and efficiently controlling production are parts of production management. To accomplish organizational objectives, the management operates to coordinate activities. A method to overcome the management of household waste is through BSF Bioconversion Technology, which needs a very short time compared to traditional forms (Cohn *et al.*, 2022). Moreover, the advantage of using BSFL bioconversion technology is waste media as feed material for cultivation. BSF is a source of animal and fish feed because the protein content is not relatively different from soybean meal (Luperdi *et al.*, 2023). Therefore, it is very prospective as a feed ingredient, especially for poultry. This is a great opportunity to replace soybean meal with BSF flour as a source of animal feed which is relatively cheaper. The potential of BSF flour is not only as poultry feed but also as fish feed. It can also be used as ornamental animal feed for birds, reptiles, cats, and fish. To further increase profits, BSF cultivation business needs to be integrated with poultry, fish, and agricultural farming businesses. This is because solid and liquid fertilizers produced are very good for plant and reduces inorganic fertilization costs (Rehman *et al.*, 2023). Therefore, BSF bioconversion technology is an integrated circular solution that can provide sustainability food and feed. It is necessary to increase understanding of good and correct BSF cultivation management by avoiding growing media from heterogeneous organic waste contaminated with heavy metals and toxic chemicals.

Technological dimension

The technological dimension had a comparatively high sustainability index score of 74.74%, according to the current investigation. Therefore, the technological effects of producing BSFL are extremely sustainability, as shown in Table 6. The greatest influence on sustainability was from management expertise and abilities in BSFL generation. Another significant factor with a favorable impact on job prospects for the local people involved in the production is the accessibility of BSFL-producing facilities.

Sustainability of BSFL productivity is influenced by the availability of capital, human resources, and technology. For BSFL production on a small scale, productivity standards are used to evaluate the effectiveness of the workforce, businesses, or systems to convert inputs into desired outputs. To produce sustainability BSFL, it is necessary to pay attention to the level of productivity, and the importance of selecting and obtaining leftover feed as raw materials to produce high-quality products and management levels. Planning, organizing, directing, and efficiently managing production are all parts of the management. BSF technology is an environmentally friendly and low-cost method due to its fast transition rate, high sustainability, and low cost-effectiveness compared to existing and other operational technologies (Salam *et al*., 2021). Furthermore, sustainability of BSF cultivation can be improved by performing some aspects of key areas which can be addressed, such as feedstock selection, energy efficiency, water conservation, waste reduction, and potential disease management. The development of BSFL production for different applications such as animal feed, fertilizer, and waste disposal involves several technical issues. Some of the key technical aspects to consider when developing a BSF are *a). Habitat design*: BSFL needs specific environments to thrive, and habitat design must provide optimal conditions such as temperature, humidity, and light. Meanwhile, BSF and housefly (HF) larval setups were fed poultry manure aged 0-8 days at 16 hours of light and 8 hours of darkness, with temperature of 26°C, and 70% relative humidity (Miranda *et al*., 2019). *b). Feeding system*: BSF biomass development requires a consistent food source, and feeding systems must be designed to provide optimal nutrition while maintaining cleanliness and preventing contamination (Meneguz *et al*., 2018). Manojkumar *et al*., (2023) indicated that cauliflower (*Brassica oleracea*) as well as the species of seaweed *Sargassum myriocystum* (Balaraman *et al*., 2022) contain substances used as bactericidal or larvicidal. Therefore, these plants can endanger the life of BSFL and should not be used as a food source. *c). Harvest*: Harvesting BSF biomass can be a difficult task and the techniques used must be efficient and cost-effective. Furthermore, the harvesting system must reliably separate larvae from substrate and other contaminants. The method should be designed according to the intended use of the biomass and the processing method. For example, when BSF biomass is to be used as animal feed, processing methods should ensure the larvae are pathogen-free and safe for consumption (Gold *et al*., 2021). *d). Automation*: This technology increases efficiency, reduces labor costs, and ensures consistent quality of BSFL (Vuoang, 2019). *e). Waste management*: Waste is generated during the production of BSFL, and the management systems should be designed to prevent pollution and ensure sustainability (Amrul *et al*., 2022). *f). Quality management*: Quality control measures should be taken to ensure that BSFL biomass meets the standards required for the intended use. This may include regular testing for nutrients, moisture, and contamination. Developing BSF biomass requires careful consideration of several technological points to ensure optimal production and sustainability (Siddiqui *et al*., 2022). In addition, assessing the quantity of BSF in a sustainability study can be conducted by several methods by counting the larvae, measuring the growth rate (Meneguz *et al*., 2018) and biomass (Smetana *et al*., 2019), and estimating the population density (Surendra *et al*., 2020).

Environmental dimension

The lowest attribute is efficiency in the use of materials for the production of BSF biomass and compost by 0.41 as shown in Fig. 2. This dimension can be improved with an organic waste processing program through regular and comprehensive training and coaching conducted by the empowerment organization to improve the capabilities of its human resources and make the community more active and empowered in organic waste processing activities. This is conducted through cultivation which produces BSF for animal feed and compost from manure.

Social dimension

The lowest attribute is management education level at 0.16, as shown in Fig. 3. After the community is given education and guidance on waste management with BSF biomass cultivation, the economic business group can be assisted in its implementation. Therefore, BSF biomass production scale becomes increased with more organic waste.

Economical dimension

The weaknesses in Fig. 4 include the attribute market level absorption of BSF production (0.00037), the efficiency level of obtaining row materials (0.00038), the efficiency of row production materials (0.00037), contribution to improving the welfare of managers or workers (0.00038), and a potential increase in business scale and production management level (0.00047). Furthermore, improvements in the economic dimension can be made through cooperatives to play an active role in improving and maintaining price stability.

Technological dimension

The weakest technological dimension is the attribute of the success rate of adopting BSF production system for the surrounding community at 4.41, as shown in Fig. 5. These weaknesses can be overcome by maximizing the potential starting from adequate facilities and infrastructure, developing BSF which can be used for fish and livestock feed. In this case, Village Owned Enterprises must assume a role in management and marketing. Additionally, it is imperative to establish cooperation with BSF cultivators and the farming community to enhance sales and foster a sense of community encouragement. In addition, all dimensions need to be fully supported by the Regency Government, especially the Environment and Sanitation Service and several related agencies. Therefore, the implementation is more effective to reduce the amount of waste, especially organic waste. It is imperative to diversify the processing technology of BSF in a manner that can extend its shelf life, thereby ensuring greater market absorption. One approach to achieve this goal is the production of BSF biomass flour.

CONCLUSIONS

MDS method was used to calculate the level of sustainability of BSF cultivation, where the dimensions and attributes are determined by identifying the influence of each dimension. Furthermore, environmental, social, economic, and technological dimensions were determined. The approach of Rapfish software was used to evaluate the scientific viability of the biorefinery method employed in the manufacture of BSFL. Sustainability index of biomass production was estimated to be 89.69%, hence the process has the potential for sustained development when the leverage factors described in each dimension are considered. Analysis showed that the economic dimension had the highest leverage value of 100%. The environmental and social dimensions had a value of 92.02% with the highest attribute being the potential for air pollution generated and involvement of family members in maggot cultivation by 7.8% and 7.98%. The lowest is the technological dimension with a value of 74.74%. Competencies and experiences in management, family member involvement, and productivity level need to be improved to increase sustainability of BSF biomass production. Finally, Quality control measures should be considered to ensure that BSFL biomass meets the standards required for its intended use. Developing BSF biomass requires careful consideration of several technological points to ensure optimal production and sustainability. In the future, BSF cultivation has the potential to be developed because of the increasing need for animal feed. Moreover, national protein requirements represent a crucial element in animal feed, serving as a vital source of nutrition for body growth and brain development. BSF cultivation produces organic fertilizers rich in nutrients required by agricultural countries using the potential of "organic waste" resources.

AUTHOR CONTRIBUTIONS

A.D. Santoso performed the literature review, experimental work, drafting of the manuscript, obtaining funding, interpretation of MDS data and made critical revision of the manuscript for important intellectual content; T. Handayani performed the literature review, designed the study, drafting of the manuscript, experimental work and made critical revision of the manuscript for important intellectual content; R. A. Nugroho performed drafting of the manuscript, and supervised all experiments and manuscript preparation; A.I.

Yanuar performed analysis and interpretation of MDS data, experimental work, statistical analysis and supervised manuscript preparation; Nadirah performed the literature review, experimental work, manuscript preparation and critical revisions; E. Widjaja performed the literature review, manuscript preparation, analysis and interpretation of MDS data, critical revisions and supervised manuscript preparation; E.S. Rohaeni performed the literature review, manuscript preparation, analysis data, interpretation of MDS data, critical revisions and supervised manuscript preparation; M.A.M. Oktaufik performed analysis and interpretation of MDS data, experimental work, and supervised statistical analysis; U. Ayuningtyas supported the administrative, technical, or material support; Y.P. Erlambang supported the administrative, technical, or material support; R. Herdioso performed analysis and interpretation of MDS data, and statistical analysis; M.N. Rofiq performed the literature review, analysis and interpretation of MDS data, statistical analysis, experimental work, and supervised manuscript preparation; R. Hutapea performed the literature review, experimental work, manuscript preparation and critical revisions; A.L. Sihombing performed the literature review; B. Rustianto performed the literature review; I.M.A.D. Susila performed the literature review, and acquisition of data BSF production; D. Irawan supported experimental and administrative work, provided technical and material assistance; D. Iskandar performed the literature review and acquisition of data BSF production; S. Indrijarso performed the literature review and acquisition of data BSF production. G.D. Widiarta supported experimental, administrative work and provided technical assistance.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
ASCAL	Alternating least-squares algorithm
BSF	Black soldier fly
APHA	American public health association
BSF frass	Material organic fertilizer from solid excreta of BSF
BSFL	Black soldier fly larvae
C	Carbon
CH_4	Methane
C/N ratio	Carbon-nitrogen ration
CSR	Corporate social responsibility
d	Euclidian distance
d_{ij}	Euclidian distance from point i to point j

d_{ijk}	Squared distance
FW	Food waste
FAO	Food and agriculture organization
GDP	Gross domestic product
H	Hydrogen
HF	House fly
kg	Kilogram
LCA	Life cycle assessment
Ltd	Limited
Maggot	BSF larvae
MC	Moisture content
MDS	Multidimensional scaling
mg	Miligram
$mgCH_4/kg$	Miligram methane per kilogram substrate
N	Nitrogen
NA	Not applicable
O	Oxygen
pH	Potential of hydrogen
ppm	Part per million
Rapfish	Rapid appraisal for fisheries, an analytical method to assess the sustainability of fisheries based on a multidisciplinary approach
RH	Relative humidity
RMS	Root mean square, a frequently used measure of the differences between values
S	Sulphur
SR^2	Squared correlation
SQR	Structured query reporter, a programming language designed for generating reports from database management systems
TKN	Total Kjeldahl Nitrogen
TS	Total solid
USD	United states dollar
VS	Volatile solid
ww	Wet weight
x-axis	Horizontal number line
y-axis	Vertical number line

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